# QUANTIFICATION OF CYCLIC GROUND REACTION FORCE HISTORIES DURING DAILY ACTIVITY IN HUMANS

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Introduction: Theoretical models and experimental studies of bone remodeling suggest that bone density and structure are influenced by local cyclic skeletal tissue stress and strain histories. Estimation of long-term loading histories in humans is usually achieved by assessment of physical activity level by questionnaires, logbooks, and pedometers, since the majority of lower limb cyclic loading occurs during walking and running. These methods provide some indication of the mechanical loading history, but fail to consider the true magnitude of the lower limb skeletal forces generated by various daily activities. These techniques cannot account for individual gait characteristics, gait speed, and unpredictable high loading events that may influence bone mass significantly.

We have developed portable instrumentation to measure and record the vertical component of the ground reaction force ($GRF_Z$) during normal daily activity. This equipment allows long-term quantitative monitoring of musculoskeletal loads, which in conjunction with bone mineral density assessments, promises to elucidate the relationship between skeletal stresses and bone remodeling.

Methods: The $GRF_Z$ monitoring system consists of a single capacitance insole force sensor and signal conditioner (EQ; Plymouth Meeting, PA) coupled with a battery-powered data logging system (Tattletale; Onset Computer; North Falmouth, MA) interfaced to a 2-megabyte RAM card and LCD display. $GRF_Z$ data are sampled continuously at a rate of 100 Hz. For short-term high-resolution studies, force data are stored directly to RAM for off-line analysis, allowing for a maximum of 3 hours of data collection. For long-term studies, a real-time filtering algorithm stores only significant data peaks and valleys to RAM, increasing the data capacity to approximately two weeks duration. A record of peak loading rate between each peak and valley and a histogram of time at force are also retained in real time. The signal conditioner and data logging system are packaged together in a single unit, 1.5" x 2.5" x 5", which is worn on a belt around the waist.

A "rainflow" algorithm [2] is used to categorize each significant $GRF_Z$ cycle in terms of its magnitude (range) and offset from zero. These data are presented as range-offset histograms such as those in Figures 1a-b, which summarize data collected from one subject over a typical 40-hour laboratory work week, and over 40 minutes of walking/running outdoors, respectively. These plots are effective tools to visualize cyclic loading histories associated with various activities.

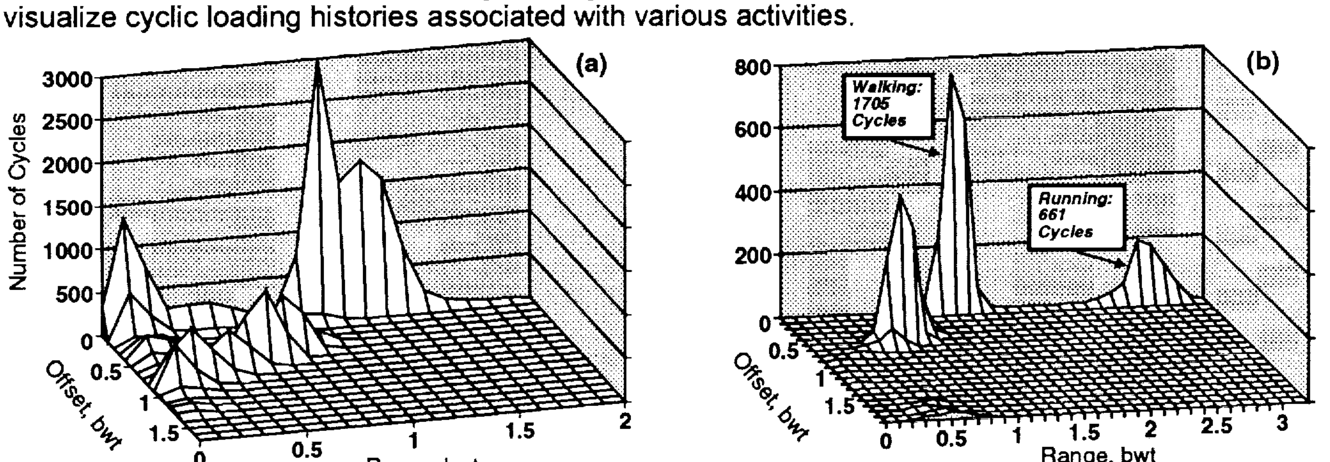


**Figure 1a-b:** Range/Offset histograms summarizing cyclic loading histories for two types of activity: (a) 40 hours of sedentary laboratory work; (b) 40 minutes of walking/jogging. The vertical axis indicates the total number of cycles which occurred at a particular range and offset. Cycles which occur at an offset of zero and possess a range ≥1 body weight (bwt) are associated with gait, with those cycles in excess of 1.8 bwt attributed to running. An electronic step counter worn during data collection for Figure 1b indicated that 2390 steps were taken, which differs by 1% from the total of 2366 found by counting cycles. Cycles offset from zero with ranges <1 bwt usually occur midstance during walking and running.

We have recently developed an alternative approach to logging cyclic $GRF_Z$ loads during human gait that overcomes limitations due to nonlinearity and fatigue in the force sensors. During walking or running, the principal determinant of peak ground reaction force, from cycle to cycle, is the gait velocity. In general, an increase in gait speed results in higher peak $GRF_Z$, *as well as* a concomitant decrease in the foot-ground contact time [1]. In other words, increased walking and running speed results in a taller, narrower $GRF_Z$ time profiles during the contact phase of the gait cycle. Consequently, we hypothesized that during gait, contact times are reliable indicators of peak $GRF_Z$, and can be used in lieu of direct force measurements to determine cyclic loading histories during daily activity.

For an individual subject, an empirical $GRF_Z$/contact-time relationship is established in a laboratory setting, using an instrumented force plate connected to a microcomputer equipped with data acquisition hardware and software. Subjects are instructed to walk and run over the plate at a variety of speeds. Gait speed is determined by measurement of transit time between two points of known separation. Because of the disparity between typical contact times for walking (0.5-0.8s) and running (0.1-0.35s), these two types of gait are easily distinguishable. Linear regression equations for peak $GRF_Z$ vs. contact time are calculated separately for running and walking. The regression standard error $\mathbf{s}_{yx}$ [4] is noted to account for the normal step-to-step variability of peak $GRF_Z$.

For the 40 minutes of $GRF_Z$ data summarized in Figure 1b, a step-by-step contact time history was generated by noting all time intervals between upward and downward crossings of a critical $GRF_Z$ level (≥0.2 bwt). Each interval was identified as either walking or running on the basis of its duration, and was converted to a peak $GRF_Z$ by the appropriate regression equation. To simulate the variability of these forces, a Gaussian random number of variance $\mathbf{s}^2_{yx}$ was added to each estimated $GRF_Z$.

Results:

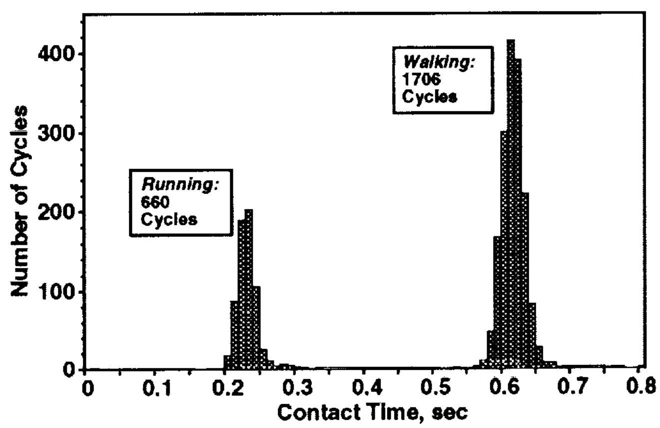


**Figure 2:** Contact time histogram for the data in Figure 1b. Characteristic times for walking and running are evident in the distribution's biphasic nature. Splitting the distribution at 0.50s, mean contact times (±SD) were 0.614±0.021s (walking) and 0.229±0.018s (running). Discrepancies in step counts from Figure 1b are attributed to errors in mapping of histogram bins.

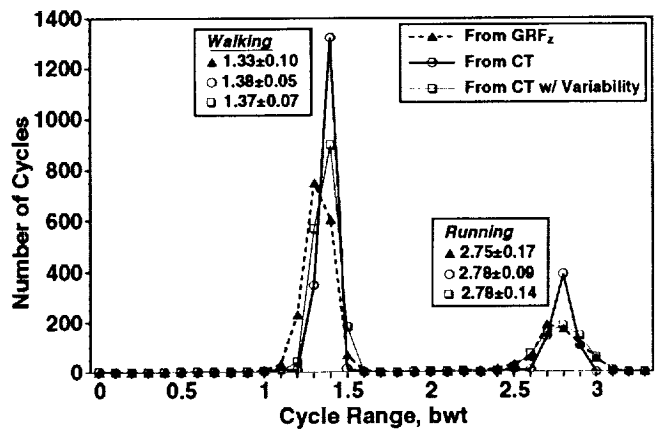


**Figure 3:** Estimated cyclic loading histories for the data shown in Figure 1b, calculated from $GRF_Z$ history, contact time history (Figure 2), and contact times plus $GRF_Z$ variability estimate. The $GRF_Z$ profile is identical to the zero-offset cross section of Figure 1b. Means ±SD (in bwt) are given for each phase of the distribution (split at 1.8 bwt).

Discussion: Current models of bone remodeling identify cyclic loading as a crucial determinant in skeletal adaptation. Accurate determination of long-term $GRF_Z$ histories may be essential to our understanding of the relationship between mechanical loads and bone remodeling and may be a useful approach to examine activity decline with age and its influence on bone density [3].

In terms of instrumentation, estimation of $GRF_Z$ cycles by means of contact times is an attractive alternative to direct force measurement. The sensor, signal conditioner, and A/D converter in our current system could be replaced by a simple binary switch, connected to a single digital input on the microcontroller. As seen in Figure 3, the cyclic loading history estimated from contact times matches closely that determined directly from $GRF_Z$ measurements--the distribution means differ by less than the histogram resolution (0.1 bwt). This approach has limitations, however. This technique does not measure static loading, such as that experienced during upright standing. Furthermore, force/contact time calibration data are collected on level ground and may be inappropriate to situations such as stair climbing or walking on inclined surfaces. Nevertheless, the loads believed to have the greatest influence on bone occur during gait over level ground, minimizing the significance of these limitations.

References:


**1.** McMahon TA and Cheng GC, The mechanics of running: how does stiffness couple with speed? J. Biomech. 23 (Suppl. 1): 65-78, 1990. **2.** Nelson DV and Fuchs HO, Predictions of cumulative fatigue damage using condensed load histories. In: Fatigue under Complex Loading. (R.M. Wetzel, ed.) SAE, Warrendale, PA. 1977. **3.** Whalen RT, Carter DR and Steele CR, Influence of physical activity on the regulation of bone density. J. Biomech 21:825-838, 1988. **4.** Zar JH, Biostatistical Analysis. 2nd ed. Sec. 17.3. Prentice-Hall, Englewood Cliffs, NJ. 1984.